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Energy dissipating shear key for precast concrete girder bridges

A. Vasseghi

International Institute of Earthquake Engineering and Seismology, No. 21, Arghavan St., North Dibajee, Farmanieh, Tehran, Iran

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KEYWORDS
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Bridge;
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Abstract This paper presents an economical solution to improve the seismic response of simply supported precast concrete girder bridges under transverse excitation. This solution employs an energy dissipation system, which consists of conventional elastomeric bearings that transfer gravity load to the substructure, and energy dissipating shear keys that replace conventional shear keys on bent caps and abutments. The proposed shear key, which is a yielding steel damper, transfers a good portion of the seismic load to the substructure, while dissipating the seismic energy through inelastic deformation. An experimental study on four full scale specimens is conducted to evaluate the behavior of the proposed shear keys under cyclic loading condition. The specimens with good ductility and energy dissipation capacity are identified. These specimens were able to sustain large inelastic deformation without any strength degradation under cyclic loading. The nonlinear time history response of a three span precast concrete girder bridge, with and without the proposed shear key, is also studied. The results of analyses indicate that seismic demands on the substructure are greatly reduced when conventional shear keys are replaced by the proposed shear keys.

1. Introduction

Bridge superstructures with precast concrete girders supported on conventional elastomeric bearings are widely used for short and medium span bridges. Concrete shear keys are commonly used at the abutments and interior bents of such bridges to provide transverse support for the bridge superstructure. The shear keys, which are usually placed between longitudinal girders of the superstructure, transfer the transverse seismic load to the substructure. Conventional concrete shear keys usually have high rigidity and low ductility, and hence they transfer a large lateral load to the substructure with little energy dissipation. To improve the seismic performance of such bridges, a ductile steel shear key, with a high energy dissipating capacity, is proposed as an alternative to the concrete shear key. Such shear keys serve as structural fuses to protect the bridge substructure under transverse seismic loads. The structural damage would concentrate within the proposed shear keys, which could easily be replaced with no interruption to the traffic. This is consistent with the design philosophy of modern bridge design codes [1–3] that allow inelastic response and structural damage at locations within the bridge that can be repaired without closure.

The retrofit of a seismically deficient bridge could also be easily achieved by conversion of the existing concrete shear keys to ductile steel shear keys. This scheme is particularly desirable, as it requires minimum retrofit to the bridge structure and no interruption to the traffic on the bridge. Figure 1 shows the application of such shear keys for the seismic retrofit of existing bridges. As shown in this figure, the steel shear keys would be placed between the girders and anchored to bent caps and abutments, while the concrete shear keys are disengaged by removal of their outside edges.

The proposed shear key is actually a steel hysteretic damper that dissipates seismic energy by flexural yielding of the steel material. The idea of utilizing a steel hysteretic damper within a structure to dissipate seismic energy began in the early 1970's [4,5], since which time, a wide variety of hysteretic dampers that dissipate energy by flexural, shear or extensional plastic deformation of steel materials has been studied [6–20]. One such device, which uses X-shaped steel plates, is the Bechtel Added Damping and Stiffness (ADAS) device. This device is designed to dissipate energy through the flexural yielding deformation of X-shaped steel plates configured in parallel

E-mail address: vasseghi@iiees.ac.ir.

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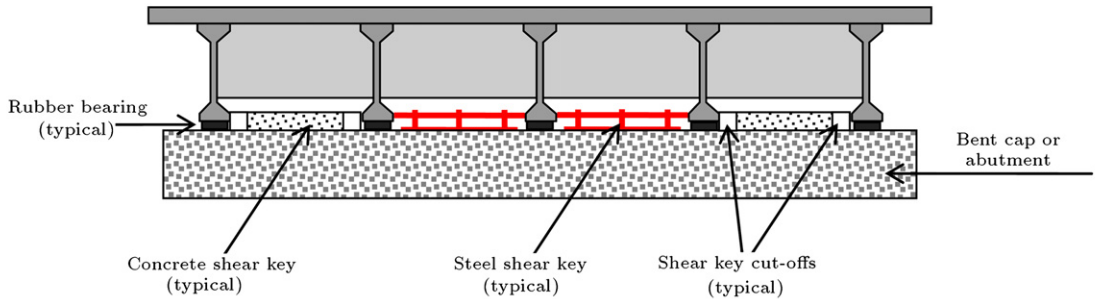


Figure 1: Application of steel shear keys for seismic retrofit of bridge.

Figure 2: Typical steel shear key prepared for testing.

between top and bottom boundary connections. The behavior of ADAS devices and their application in various structures has been extensively studied [12–20]. Some particularly desirable features of ADAS devices are their stable hysteretic behavior, low-cycle fatigue property, long term reliability and relative insensitivity to environmental conditions. Their main shortcoming is that the hysteretic behavior is adversely affected when subjected to axial load.

The proposed shear key consists of several parallel X-shaped steel plates that are connected to a rectangular steel plate at the bottom and to a steel member at the top. Figure 2 shows a typical sample with three X-shaped plates. The bottom steel plate would be anchored to abutments and bent caps by anchor bolts, such that the two ends of the top steel member are just next to the bridge girders. Lateral displacement of the superstructure during an earthquake would impose a cyclic load on X-shaped plates. When seismic intensity and consequently lateral displacement of the superstructure exceed a certain limit, the X-shaped plates would deform inelastically and dissipate the seismic energy through flexural yielding. The particular advantage of an X-shaped plate is that when deformed in double curvature, plate deformation is uniform over its height, and yielding is spread almost uniformly throughout the material. They are most effective when little or no axial load is applied to them. In this application, the plates would not be subjected to any axial load.

2. Experimental study

The experimental program consists of four full scale tests of steel shear keys under cyclic loading. Figure 3 shows the shop drawing of the specimens. Each specimen has three 2 cm thick X-shaped plates. These plates are connected to a 140 cm $\times$ 24 cm $\times$ 2 cm bottom plate by full penetration welds. At the top, the plates are connected to a 10 cm $\times$ 5 cm $\times$ 0.5 cm structural tubing member.

The only difference between the specimens is the way the top structural tubing member is connected to the X-shaped plates. In two of the specimens (A and B) the tops of the X-shaped plates are perforated and the top tubing member is passed through the perforated plates in one piece. In the other two specimens (C and D) the X-shaped plates are not perforated and the top tubing member is connected to them in four pieces. In all cases, a 5 mm fillet weld is used to connect the tubing member to the plates. Figure 4 shows the X-shaped plates for the two cases.

The dimensions of the shear keys are the same in all specimens. The dimensions of the X-shaped plates are optimized for a nearly uniform yielding within the reduced section.

Figure 5 shows the test set-up. In each test, the bottom plate is bolted to a rigid pedestal and cyclic displacement is applied to each end of the top tubing member by an actuator. Figure 6 shows a picture of one of the specimen during testing. Positive displacement is applied to the left end directly by the actuator and negative displacement is applied to the right end through an end plate and four rods connected to the actuator.

2.1. Experimental results

Figure 7 shows the load deflection curves for the specimens with perforated X-shaped plates. Both specimens exhibited stable behavior with little loss of strength up to a displacement amplitude of 36 mm. There were minor strength degradations at larger displacements. Both specimens failed at the displacement amplitude of 48 mm. This displacement is 12 times the yield displacement of 4 mm. In both cases, failure was due to a fracture in one of the plates at the corner of the perforated hole. Figure 8 shows a picture of such a fracture.

Figure 9 shows the load deflection curves for the specimens C and D, where X-shaped plates were not perforated. Comparison of these curves with the load deflection curves in Figure 8 indicates that the energy dissipation capacities of these specimens are better than those with perforated plates. Specimen C exhibited stable behavior without any strength degradation up to displacement amplitude of 48 mm. The test was ended without any failure. The applied load, at a displacement of 48 mm, was about 30% larger than the corresponding loads in specimens A and B. Specimen D showed essentially the same behavior up to a displacement of 48 mm. The cyclic loading of this specimen continued at a displacement amplitude of 56 mm, which is equivalent to 14 times the yield displacement. At this displacement and during the third cycle of loading a fracture occurred along a full penetration weld connecting one of the X-shaped plates to the bottom plate. Figure 10 shows a picture of the failure.

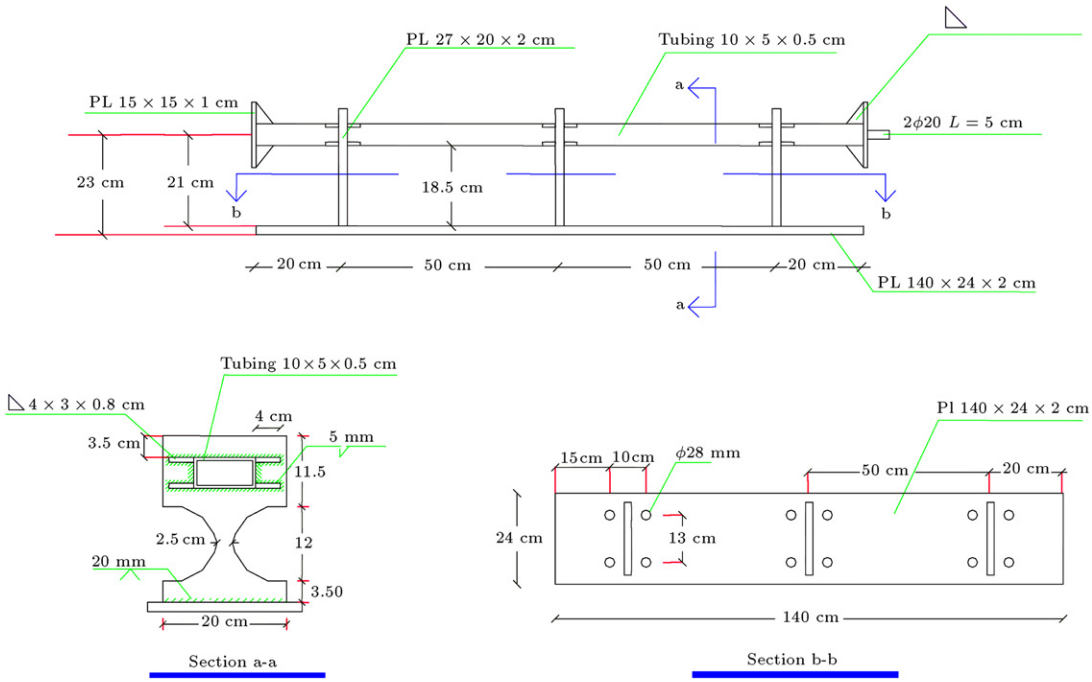


Figure 3: Dimensions of specimens.

(a) Specimens A and B. (b) Specimens C and D.

Figure 4: X-shaped plates.

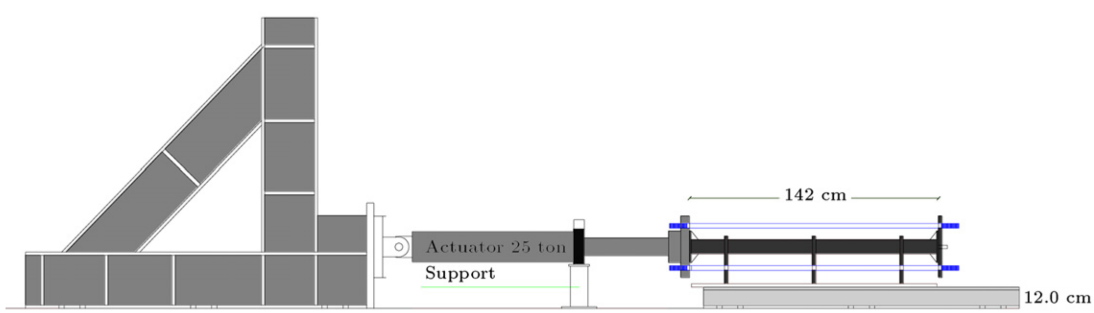


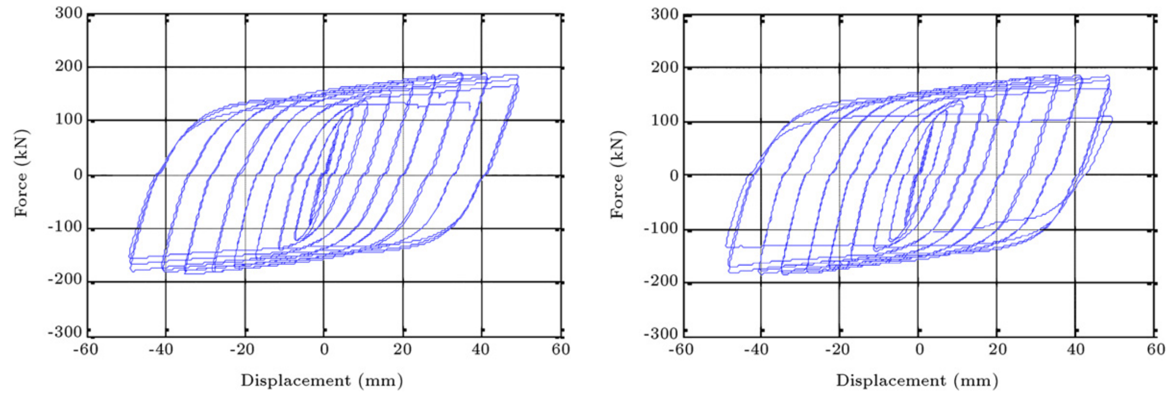
Figure 5: Test set-up.

Figure 6: Picture of typical specimen during testing.

3. Analytical study

A three span precast concrete girder bridge, with equal spans of 30 meters, is considered for seismic analysis under transverse excitation. The superstructure is 11.8 meters wide and carries two traffic lanes. Figure 11 shows the cross section of the superstructure and Figure 12 shows the dimensions of the girders. The girders are simply supported and connected to each other by three transverse diaphragms at the mid-span and at each end.

The girders are supported on 400 mm × 400 mm steel reinforced elastomeric bearings at each end. Each bearing



(a) Specimen A.

(b) Specimen B.

Figure 7: Load displacement curves for specimens A and B.

Figure 8: Fracture failure in specimen B.

consists of two exterior layers with 6 mm thickness, four interior layers with 12 mm thickness and five 2 mm steel reinforcement. The stiffness properties of the bearing are as follows: Vertical stiffness: $k_v = 3227000$ KN/m.

Shear stiffness: $k_u = 5220$ KN/m.

Rotational stiffness: $k_r = 1420$ KN/m.

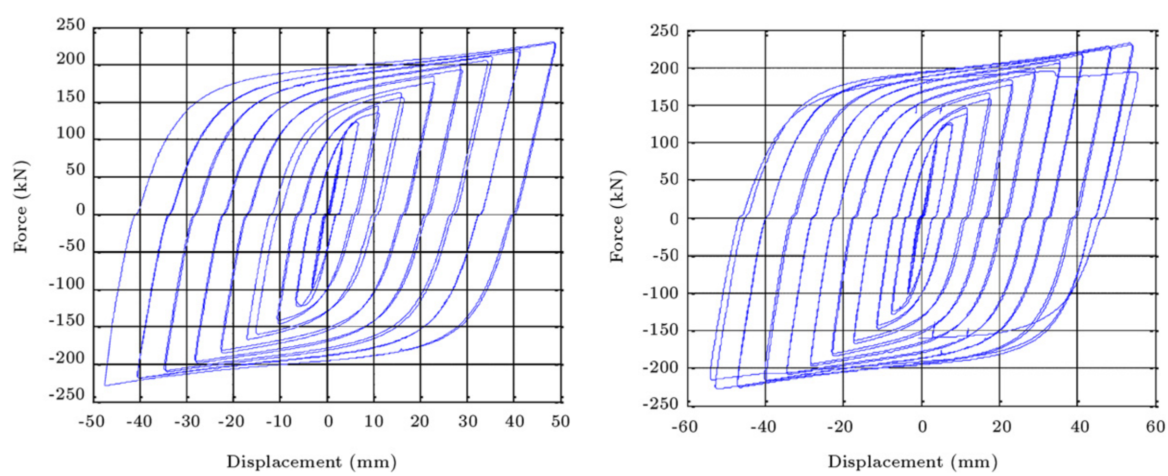
Torsional stiffness: $k_t = 118$ KN/m.

The substructure consists of two closed end seat type abutments and two interior bents. Each bent consists of three concrete columns with a diameter of 1.2 meters. The columns, which are rigidly connected to a pile cap, are 7.75 meters tall. Figure 13 shows details of the interior bent. Two concrete shear keys on each bent cap and abutment restrain the transverse displacement of the superstructure.

3.1. Description of FEA model

Figure 14 shows the FEA representation of the bridge. The bridge superstructure is modeled by a combination of frame elements for the girders and shell elements for the slab. The shell elements are vertically offset to locate them at their actual location within the structure. The columns and bent caps are modeled using frame elements. The columns are fixed at the pile cap interface. The abutments are assumed to be rigid.

The elastomeric bearings are modeled by spring elements with appropriate stiffness properties in all six degrees of freedom. At the interior bent, the springs representing the bearings are horizontally offset using rigid elements, in order to position them at their actual locations. They are also vertically



(a) Specimen C.

(b) Specimen D.

Figure 9: Load displacement curves for specimens C and D.

Figure 10: Fracture failure in specimen D.

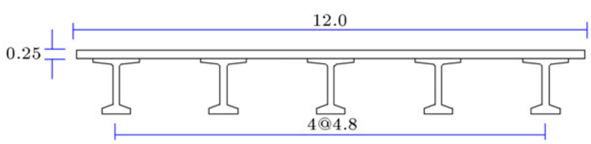


Figure 11: Cross section of bridge superstructure.

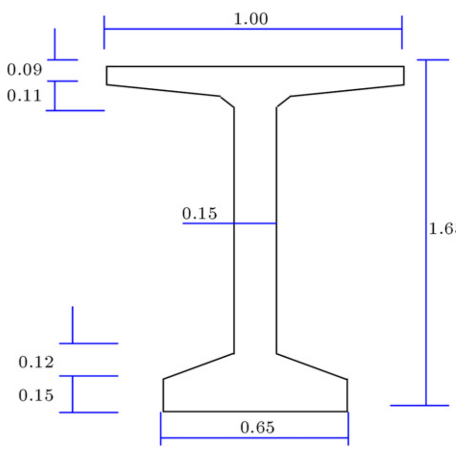


Figure 12: Typical cross section of concrete girder.

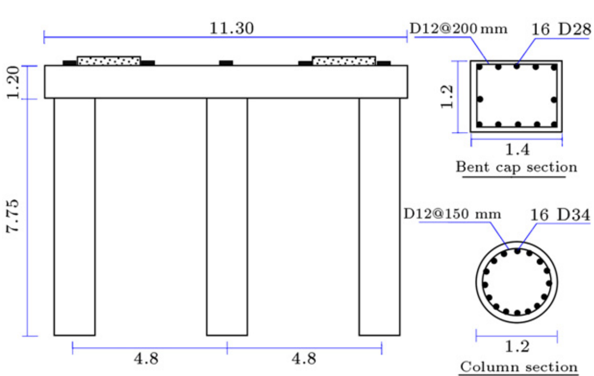


Figure 13: Interior bent.

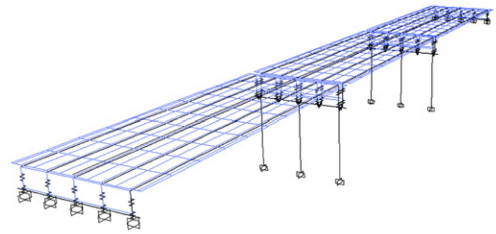


Figure 14: FEA representation of bridge.

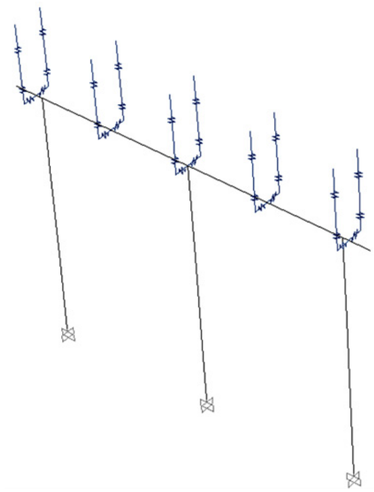


Figure 15: FEA representation of interior bent.

offset to the top surface of the cap beam. Figure 15 shows the FEA representation of the interior bent and bearings.

The seismic performance of the bridge is studied once with a concrete shear key and once with the proposed steel shear key. Concrete shear keys are assumed to be rigid and are modeled by constraining the transverse displacement of the superstructure to the bend caps and abutments.

The steel shear keys are modeled by nonlinear spring elements connecting the superstructure to bent caps and abutments. The numbers and properties of the shear keys are optimized for maximum energy dissipation, while limiting their deformation to a safe value of 35 millimeters. The optimum configuration consists of two shear keys at the end of each span. The shear keys on the abutment are the same as test specimens, with three X-shaped plates. The shear keys on the bent cap have five X-shaped plates.

The hysteretic behavior of the shear key is represented by the Wen plasticity model [21]. The model is defined by:

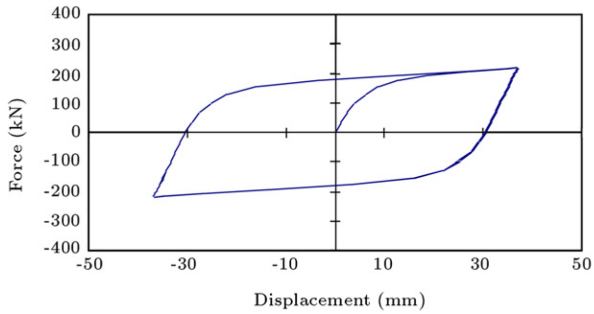
$$P(t) = \beta K u(t) + (1-\beta) F_y Z(t),$$

where K = elastic stiffness; F_y = yield strength; β = ratio of post-yield stiffness to elastic stiffness and $Z(t)$ = a variable that is defined by:

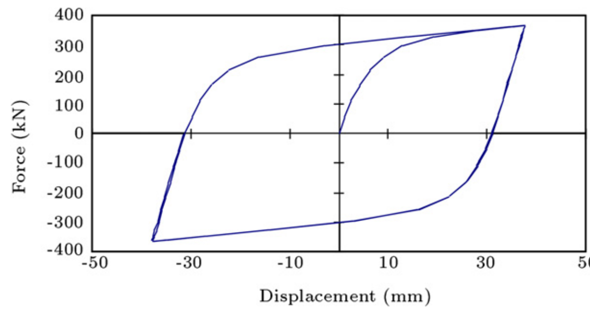
$$u_y \dot{Z}(t) + |\dot{u}(t)| Z(t) |Z(t)|^{\alpha-1} + \dot{u}(t) |Z(t)|^{\alpha} - \dot{u}(t) = 0.$$

α is a dimensionless parameter greater than or equal to unity, which defines the shape of the hysteretic loop. The transition from elastic to inelastic behavior is sharp for larger values of α. The sharpness decreases with decreasing values of α.

Table 1 lists the parameters used in the Wen model to represent the shear keys on the abutments and bent caps. The parameters for the shear key with three X-shaped plates are chosen based on test results. For the shear key

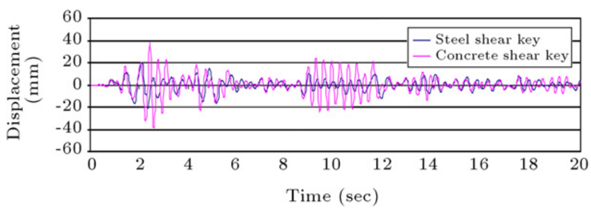


(a) Three X-shaped plates.

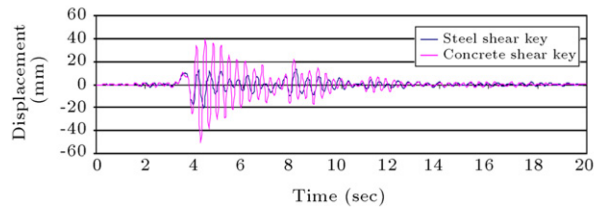


(b) Five X-shaped plates.

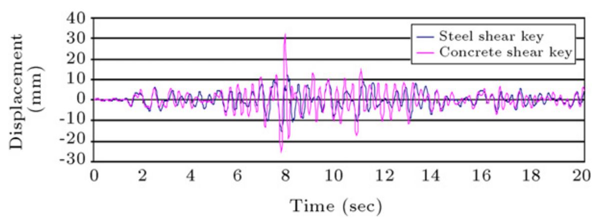
Figure 16: Load deformation curve of nonlinear springs representing steel shear keys.



(a) El-centro.



(b) Northridge.



(c) Tabas.

Figure 17: Displacement time history at top of interior bent.

Table 1: Wen plasticity parameters for the shear keys.

Shear key	K (KN/m)	F_y (KN)	β	α
Three X-shaped plate	33,833	186	0.03	1
Five X-shaped plate	56,388	310	0.03	1

with five X-shaped plates, yield strength and stiffness are increased proportionally. The load deformation relationship of the nonlinear springs representing the steel shear keys is shown in Figure 16.

3.2. Results of analytical study

The analyses consisted of static push-over analysis to determine the capacity, and dynamic time history analysis to determine the demand under transverse seismic excitation. The earthquake records of El-Centro, Northridge and Tabas, scaled to Peak Ground Acceleration of 0.6 g, are used for the time history analyses. Due to the symmetrical nature of the bridge structure, the seismic responses of the two interior bents, as well as the two abutments, are the same. Figure 17 shows the time history displacements of the bent caps for the three earthquakes. As shown in this figure, transverse displacements of the interior bents reduce significantly when steel shear keys are used instead of concrete shear keys.

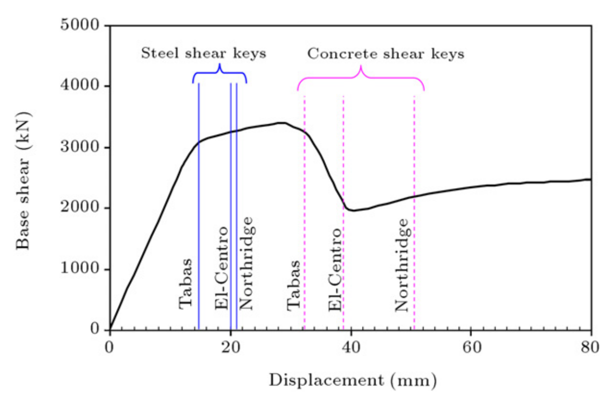
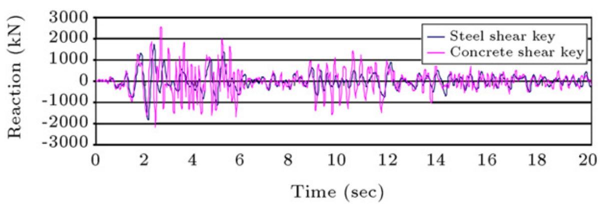
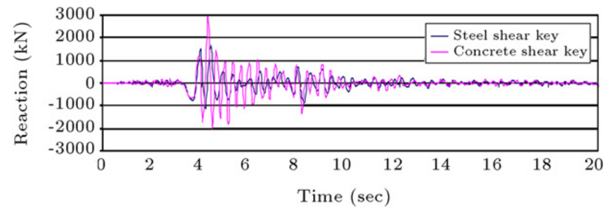


Figure 18: Displacement capacity and demand of interior bent.

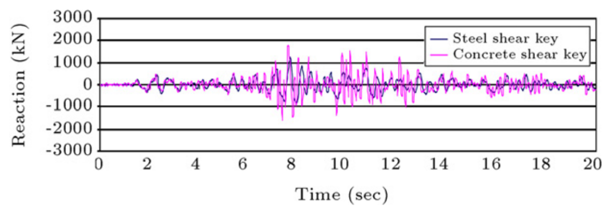
Figure 18 shows the displacement capacity curve, along with the peak displacement demands of the interior bents, for each earthquake. The capacity starts to decline at 30 mm displacement, due to the flexural-shear failure of the bent cap. For the cases associated with concrete shear keys, the peak displacement demands are between 32.2 mm and 51.0 mm. At these displacements, flexural-shear failures occur in the bent cap. For the cases associated with steel shear keys, the peak displacement demands are between 15.3 mm and 20.6 mm. These displacements are well below the displacement associated with



(a) El-centro.



(b) Northridge.



(c) Tabas.

Figure 19: Abutment reaction time history.

Table 2: Peak abutment reaction.

Earthquake	Reaction (KN)		Reduction (%)
	Concrete shear key	Steel shear key	
El-centro	2565	1840	28.2
Northridge	2953	1710	42.1
Tabas	1771	1305	26.3

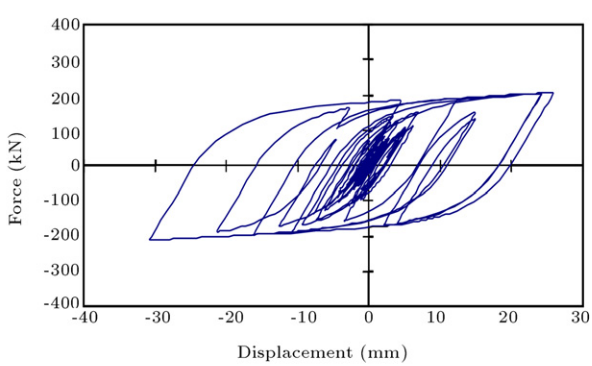


Figure 20: Typical response of steel shear key during earthquake.

the bent cap failure, and are only 1.18 to 1.58 times the yield displacement of 13.0 mm. At such displacements, no significant damage occurs within the interior bent.

Figure 19 shows the transverse reaction of each abutment during earthquakes. This figure shows that the reaction reduces significantly when the steel shear keys replace concrete ones. Reduction of peak reactions is between 26.3% and 42.1%, as indicated in Table 2.

The significant reduction of seismic demand on the bridge substructure is mainly due to dissipation of seismic energy through the hysteretic behavior of the steel shear keys. Figure 20 shows the typical hysteretic response of a steel shear key during an earthquake. It indicates the substantial energy dissipation capacity of the shear key during an earthquake.

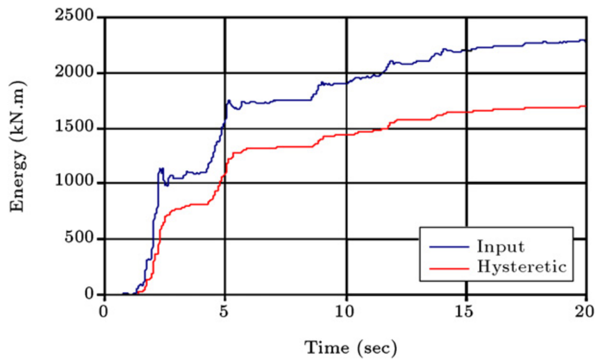
Figure 21 shows the total input energy in a transverse direction, and the energy dissipated by the steel shear keys. This figure shows that about 70% of the seismic energy is dissipated by steel shear keys.

4. Summary and conclusions

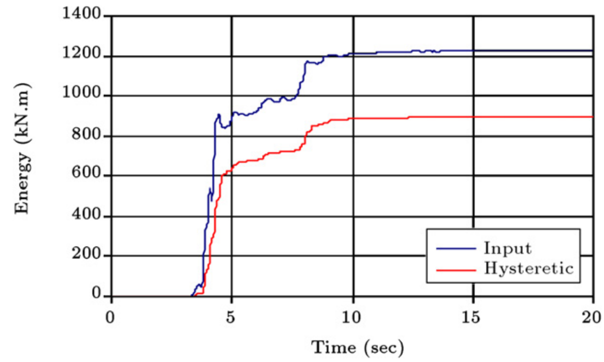
Bridge superstructures with precast concrete girders supported on conventional elastomeric bearings are widely used for short and medium span bridges. To improve the seismic performance of such bridges, steel shear keys with a high energy dissipating capacity are proposed to replace conventional concrete shear keys on bent caps and abutments. The proposed shear key is an ADAS device, which consists of several X-shaped plates connected to a rectangular plate at the bottom, and a structural tubing member at the top. The shear keys would be installed on bent caps and abutments between longitudinal girders of the superstructure. They serve as structural fuses to protect the bridge substructure under transverse seismic excitation. Lateral displacement of a superstructure during an earthquake would impose a cyclic load on the X-shaped plates. When seismic intensity exceeds a certain limit, the X-shaped plates would deform inelastically and dissipate the seismic energy through flexural yielding.

Experimental investigation on four full scale specimens is carried out to study the behavior of the proposed shear key under cyclic loading. The only difference between the specimens is the way the top structural tubing member is connected to the X-shaped plates. In the two specimens, the tops of the X-shaped plates are perforated; the top tubing member is passed through the perforated plates in one piece and then welded to the plates. In the other two specimens, the X-shaped plates are not perforated; the top tubing member is cut to four pieces and welded to the X-shaped plate. These specimens performed better under cyclic loading than the specimens with perforated plates. They exhibited stable behavior without any strength degradation up to a displacement equal to 14 times the yield displacement.

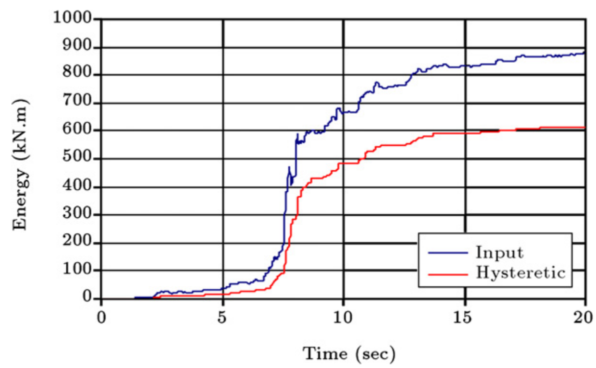
An analytical study is also carried out to evaluate the seismic performance of a three span simply supported bridge with precast concrete girders. The analytical study is performed once with ordinary concrete shear keys and once with the proposed shear keys. The analytical results indicate that the proposed shear key would substantially reduce the seismic demand of the substructure under transverse excitations.



(a) El-centro.



(b) Northridge.



(c) Tabas.

Figure 21: Total input and dissipated energy.

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Akbar Vasseghi completed his undergraduate and graduate studies at the University of Texas at Austin, where he also conducted large scale experimental research on composite plate girder bridges as part of his Ph.D. dissertation. He is currently Assistant Professor at the International Institute of Earthquake Engineering and Seismology in Iran.

His professional and research experiences include projects on Deep Water Drilling, Offshore Structures, Bridge Structures and Pipelines.